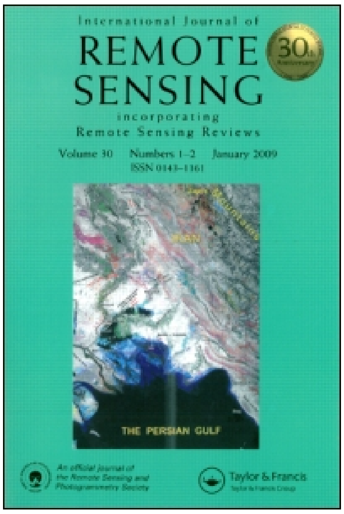

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Assessing the influence of flight parameters, interferometric processing, slope and canopy density on the accuracy of X-band IFSAR-derived forest canopy height models

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High resolution, active remote sensing technologies, such as interferometric synthetic aperture radar (IFSAR) and airborne laser scanning (lidar) have the capability to provide forest managers with direct measurements of 3-dimensional forest canopy surface structure. While lidar systems can provide highly accurate measurements of canopy and terrain surfaces, high resolution (X-band) IFSAR systems provide slightly less accurate measurements of canopy surface elevation over very large areas with a much higher data collection rate, leading to a lower cost per unit area. In addition, canopy height can be measured by taking the difference between the IFSAR-derived canopy surface elevation and a lidar-derived terrain surface elevation. Therefore, in areas where high-accuracy terrain models are available, IFSAR may be used to economically monitor changes in forest structure and height over large areas on a relatively frequent basis. However, IFSAR flight parameters and processing techniques are not currently optimized for the forest canopy mapping application. In order to determine optimal flight parameters for IFSAR forest canopy measurement, we evaluated the accuracy of high resolution, X-band canopy surface models obtained over a mountainous forested area in central Washington state (USA) from two different flying heights (6000 m and 4500 m), from different look directions, and with different interferometric processing. In addition, we assessed the influence of terrain slope and canopy density on the accuracy of IFSAR canopy height models. High-accuracy lidar-derived canopy height models were used as a basis for comparison. Results indicate that sensing geometry is the single most important factor influencing the accuracy of IFSAR canopy height measurements, therefore acquiring IFSAR from multiple look directions can be critically important when using IFSAR for forest canopy measurement applications, especially in mountainous areas.

1. Introduction

Accurate, reliable, and spatially-explicit (i.e. mapped) information relating to 3-dimensional forest canopy structure can support a wide variety of resource management applications, including timber inventory, habitat monitoring, and fire management. It has been well established that the two most important metrics in

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describing 3-dimensional forest canopy structure are canopy cover (horizontal extent of canopy), and canopy height (vertical extent of the canopy) (Paine and Kiser 2003). Foresters have long used measurements of canopy cover and canopy height to obtain estimates of stand volume from aerial photograph volume tables. Estimates of canopy height and canopy cover are also needed as inputs to fire behaviour models such as FARSITE (Finney 1998). In addition, when combined with stand age information, spatially-explicit maps of maximum canopy height can provide information relating to the growth potential for a given forest area (site index).

Active remote sensing provides an efficient means of obtaining spatially-explicit information related to canopy height and cover over large areas. Lidar remote sensing provides accurate, high-resolution measurements of canopy surface morphology and the underlying terrain (Reutebuch *et al.* 2003, Andersen *et al.* 2006). Although lidar can acquire very high-resolution (i.e. sub-metre) measurements of the forest canopy surface, it should be noted that lidar pulses do penetrate a short distance into the canopy and, therefore, lidar-based canopy measurements typically underestimate the true canopy surface height by 0.5–2 m, depending upon tree species, lidar density, laser footprint diameter, and other factors. Andersen *et al.* (2006) reported that tree height measurements obtained from lidar within a conifer forest in western Washington state, USA, had a mean error ($\pm$ standard deviation) of -1.05 ± 0.41 m for Douglas-fir (*Pseudotsuga menziesii)* and -0.43 ± 0.13 m for Ponderosa pine (*Pinus ponderosa*). Gaveau and Hill (2003) investigated the accuracy of lidar canopy height measurements in a leaf-off deciduous forest in the UK and reported that lidar underestimated tree canopy surface height by 1.27 m. Hyyppa *et al.* (2001) found a bias of -0.14 m and a root-mean-squared-error (RMSE) of 0.98 m in lidar tree height measurements of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) trees in Finland. In another investigation in Finland, Maltamo *et al.* (2004) found that lidar underestimated Scots pine tree heights by an average of -0.65 ± 0.49 m.

X-band interferometric synthetic aperture radar (IFSAR) can also provide high resolution measurements of the forest canopy surface (not the underlying terrain), but with a lower accuracy than lidar (Andersen *et al*. 2003). While lidar represents a point-like measurement of the canopy surface, IFSAR measures the height of the scattering phase centre, which represents an integrated height of all vertically distributed scattering elements within a resolution cell. In dense forest, the height of the X-band scattering phase centre will likely correspond to the top of the forest canopy, but in more discontinuous forest canopies, the error in X-band IFSAR canopy height measurements will increase (Wallington *et al.* 2004, Izzawati *et al.* 2006). However, IFSAR is typically acquired from a much higher altitude and at a higher speed than lidar, leading to significantly lower costs per unit area. Although prices for standard products (including reflectance data and derived surface models) will vary depending upon the location and size of the acquisition area, type of licence, and number of looks (or amount of overlap) acquired, the price of X-band IFSAR is in the range of \$10–50 per km^2, while lidar costs approximately \$250 per km^2. Acquiring IFSAR from multiple look directions increases the total price, but the marginal cost of each additional pass (per unit area) will decrease (Mercer B., personal communication, 2007). Therefore, if accurate terrain data have previously been acquired for a given area (e.g. from lidar) then IFSAR may provide a means of monitoring changes in forest structure at more frequent intervals than would be economically feasible with lidar. However, the accuracy of IFSAR canopy measurements is dependent upon a number of different factors, including flying height, sensing geometry, interferometric processing, terrain slope, and canopy density. The dominant source of error in X-band IFSAR elevation measurement is 'phase noise', therefore height error is largely a function of the signal-to-noise ratio (SNR) (Mercer 2004). The SNR for IFSAR measurements can be increased by acquiring the data from a lower flying height (increasing reflected signal power) or filtering the interferogram (decreasing noise power) (Mercer 2004, Rodriguez and Martin 1992). Because radar data are acquired at very shallow look angles, the accuracy of IFSAR forest canopy measurements is also significantly affected by sensing geometry and terrain relief (shadowing). Izzawati *et al.* (2006) used a simulation model to assess the influence of crown shape, density, tree height, incidence angle, and slope on the accuracy of forest height measurements from commercial X-band SAR products, and found that the most important factors were crown shape, plantation density, and tree height. In order to assess the influence of the flight parameters, interferometric processing parameters, and scene characteristics on the quality of the canopy measurements (height, cover) obtained from IFSAR, we compared canopy height measurements obtained from high density lidar to those obtained from IFSAR data collected at two different flying heights, from three different look directions, with four different levels of interferogram filtering, and over a range of slope and canopy density classes.

2. Data and methods

2.1 *Study area*

The study area for this project was a 5 km^2 area within Wenatchee National Forest, located in the Mission Creek drainage within the eastern Cascade mountains of Washington State (USA). This is a mixed-conifer forest, composed primarily of mature Douglas-fir, ponderosa pine, grand fir (*Abies grandis*), and various shrub species. This area is mountainous, with slopes in forested areas ranging from 0–50°. Since the focus of this study was on the accuracy of IFSAR canopy measurements, and not terrain measurements, a GIS polygon layer of vegetation cover type was used to isolate and restrict the analysis to the forested regions within the study area. The location and an orthophotograph of the study area are shown in figure 1.

2.2 *Lidar data*

The lidar data used in this study were acquired in the summer of 2004 with an Optech ALTM 3070† system mounted on a fixed-wing aircraft. This system acquires data with a pulse rate of 70 kHz, and provided data at a nominal density of 4 points m^{-2}.

The lidar vendor provided all-return lidar data in UTM, zone 10, NAD 83 coordinates. Ground returns were filtered by the vendor and were used to interpolate a 1 m by 1 m resolution gridded digital terrain model (figure 2). Lidar returns from the canopy surface were identified by filtering out the highest return within a 1 m by 1 m grid cell. A 1.25 m by 1.25 m resolution canopy surface model was then interpolated using these filtered, canopy-level returns.

† Use of trade or firm names in this publication is for reader information and does not imply endorsement by the USDA Forest Service of any product or services.

2.3 *IFSAR data*

IFSAR data were acquired in the summer of 2005 with the Intermap Star 3i X-band system, operating from a Lear jet aircraft platform. The wavelength for this system was 3.1 cm, and the flying speed was $720\,\mathrm{km\,h^{-1}}$.

In order to assess the effect of flying height on the accuracy of IFSAR canopy measurements, data were collected from both 15 000 ft (appox. 4500 m) and 20 000 ft (approx. 6000 m). Additionally, the IFSAR data were processed by the vendor using four different levels of interferogram filtering, or levels of oversampling (OSF). The highest level of filtering (OSF factor of 8) represents the standard (default) processing parameter for the 5-m digital surface models, and has a filtering window of slightly greater than 5 m. An OSF factor of 1 corresponds to no filtering, so the fundamental pixel size is 1.25 m, and OSF factors of 2, 4 and 8 correspond to increasing levels of filtering. Three flight lines, from one look direction, were acquired from 6000 m, and 13 flight lines, from three orthogonal look directions, were acquired from 4500 m. Three-dimensional perspective views of the lidar terrain surface, lidar canopy surface model, and IFSAR canopy surface model (combination of all looks, OSF 8, 4500 m flying height) for a selected area within the study site are shown in figures 3–5.

2.4 *Estimation of canopy height, maximum height, and canopy cover*

Lidar- and IFSAR-derived canopy height models were generated by subtracting the lidar digital terrain model from the lidar and IFSAR canopy surface models, respectively (figures 6 and 7). Estimates of canopy height and maximum height were generated at each 30 m by 30 m grid cell over the entire study area. Use of an aggregated canopy height measurement at a 30 m resolution provides GIS-ready layers and also minimizes the effect of any spatial offset between IFSAR and lidar measurements at the individual tree level. In this study, the 90th percentile surface height within a grid cell area (30 m by 30 m) was used as an estimate of canopy height. This quantile-based estimate will provide a generalized measure of canopy height within the 30 m grid cell area that will exclude measurements of non-canopy components, including bare ground and near-ground vegetation. The maximum height was simply estimated by the height of the highest surface point within the grid cell. The 90th percentile height therefore represents a generalized (i.e. smoothed) description of canopy height, while the maximum height will capture emergent canopy features. In this study, only measured elevations were included in the calculation of canopy heights—void (radar shadow) areas were excluded from the analysis. The difference between the IFSAR- and lidar-derived estimates of canopy height (90th percentile and maximum heights) at each 30 m grid cell was calculated over only the forested areas of the scene, and is assumed to represent the error in the IFSAR canopy height measurement. The distribution of IFSAR error was then described via several summary statistics (mean, standard deviation, median, and quartile deviation). Quartile deviation (QD) was computed as one half of the difference between the 75th percentile height and the 25th percentile height. Quartile deviation is a measure of variability that is less influenced by extreme observations than standard deviation. Percent canopy cover (%CC) was estimated as the percentage of surface heights within the 30 m grid cell exceeding 5 m.

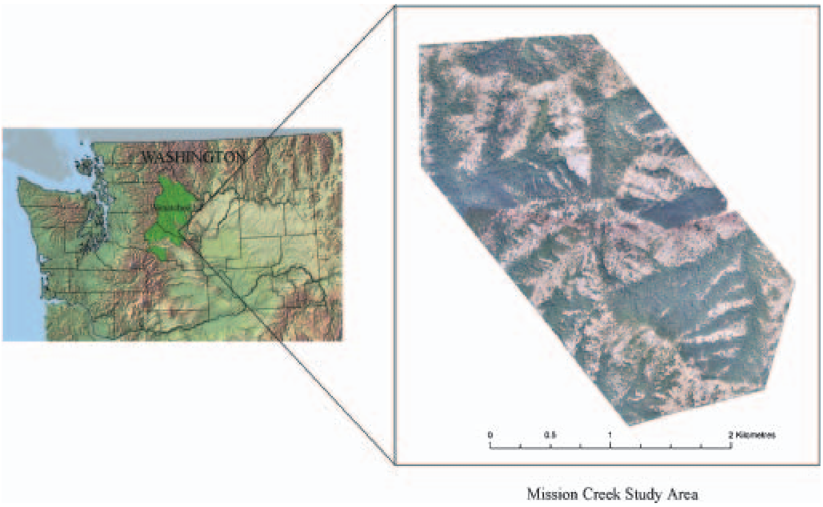

Figure 1. Location (left) and orthophotograph (right) of Mission Creek study area, Wenatchee National Forest, Washington State, USA.

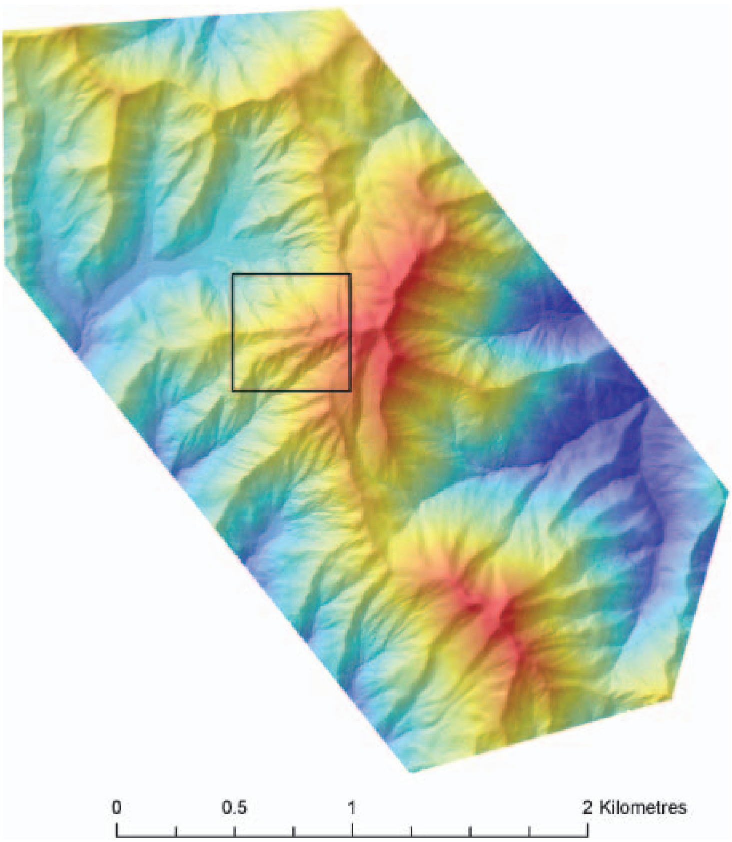

Figure 2. Lidar-derived terrain model, Mission Creek study area, Wenatchee National Forest, Washington State, USA. Colour-coded by elevation (dark red is approximately 1000 m elevation, dark blue is approximately 500 m elevation). Selected area for figures 3, 4 and 5 is delineated in black.

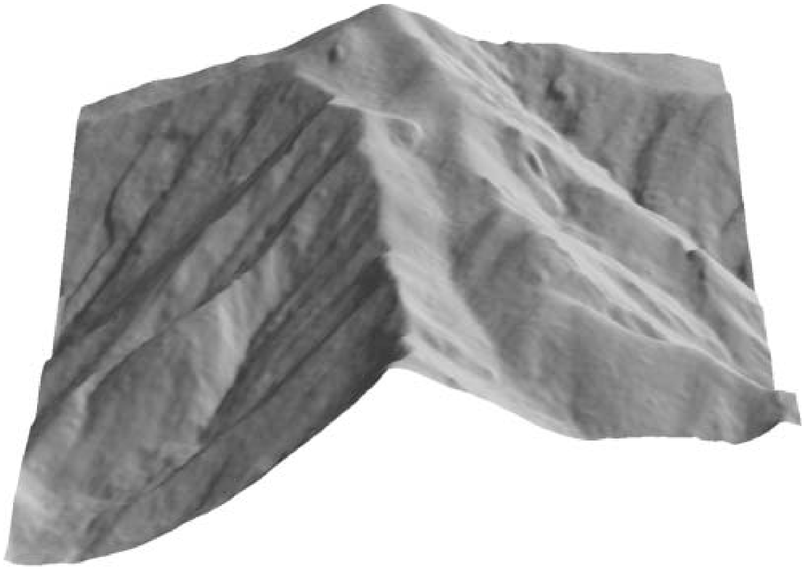

Figure 3. Lidar-derived terrain surface model for selected area (shown in figure 2) within Mission Creek study area, Wenatchee National Forest, Washington State, USA. Area is approximately 500 m × 500 m, and the view is looking west to east.

3. Results

3.1 *Influence of flying height*

The summary statistics of the IFSAR error (IFSAR height – LIDAR height) associated with single passes at 6000 m and 4500 m flying heights are shown in table 1. The study area was located close to the centre of the swath for both flight lines, and only the elevations obtained via the standard interferometric processing settings (OSF of 8) were used in the comparison.

3.2 *Influence of filtering parameters*

The summary statistics for IFSAR elevations generated using the four different levels of interferogram filtering for a single flight line are shown in table 2. Only the elevations obtained from the lower flying height (4500 m) were used in this comparison.

3.3 *Influence of sensing geometry*

A previous study has indicated that using a combination of IFSAR elevations obtained from different look directions can improve canopy height models (Andersen *et al.* 2003). In order to reduce the underestimation of canopy height due to shadowing effects, the IFSAR elevations obtained from overlapping flight lines were merged by extracting the maximum elevation within each grid cell. The error associated with the merged surfaces obtained from overlapping flight lines with the same look directions, opposite look directions, orthogonal look directions, and all look directions are compared in table 3.

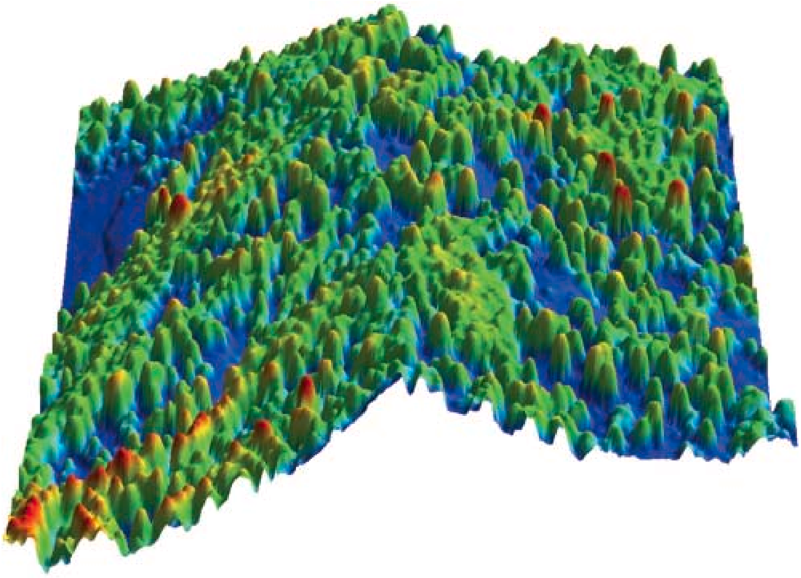

Figure 4. Lidar-derived forest canopy surface model (same area as figure 3). Colour-coded by height (blue is low canopy, red is high canopy).

3.4 *Influence of slope*

Due to the relatively shallow look angles characteristic of radar imaging, the accuracy of IFSAR canopy measurements could be influenced by terrain slope. A previous study has indicated that the influence of slope on the underestimation of

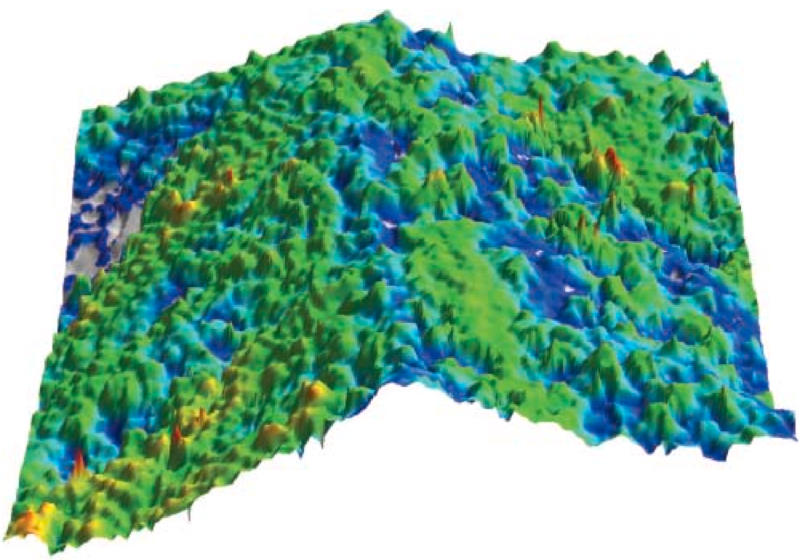

Figure 5. IFSAR-derived forest canopy surface model (same area as figure 3). Colour-coded by height (blue is low canopy, red is high canopy).

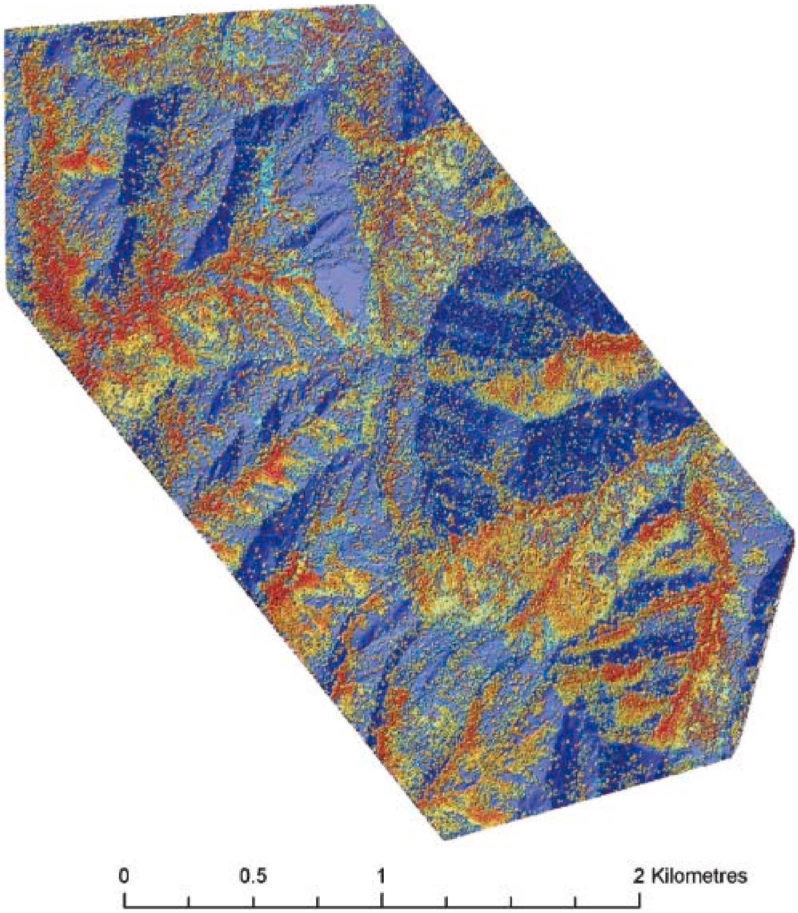

Figure 6. Lidar-derived forest canopy height model, 1.25-m resolution, draped on lidar terrain model (blue is low canopy, red is high canopy).

canopy heights in X-band IFSAR is more pronounced in low-density stands (Izzawati *et al.* 2006). In addition, it was found that the influence of slope on X-band canopy height measurements is highly sensitive to the relationship between the radar viewing angle and the local slope characteristics (Izzawati *et al.* 2006). For example, when the radar system is viewing a slope at a very high off-nadir angle, lower parts of the tree crowns are making an increasing contribution to canopy height measurements, leading to underestimation of canopy height. Therefore, it can be expected that the influence of slope on the accuracy of X-band IFSAR canopy measurements will be largely mitigated by the use of canopy models developed from multiple passes with different look directions. Table 4 shows the influence of slope on canopy height measurements for a single pass, while table 5 shows the influence of slope on canopy height measurements for surfaces obtained from all look directions.

3.5 *Influence of canopy density*

Previous studies have indicated that canopy density is a dominant factor influencing the accuracy of X-band IFSAR forest height measurements, where the degree of

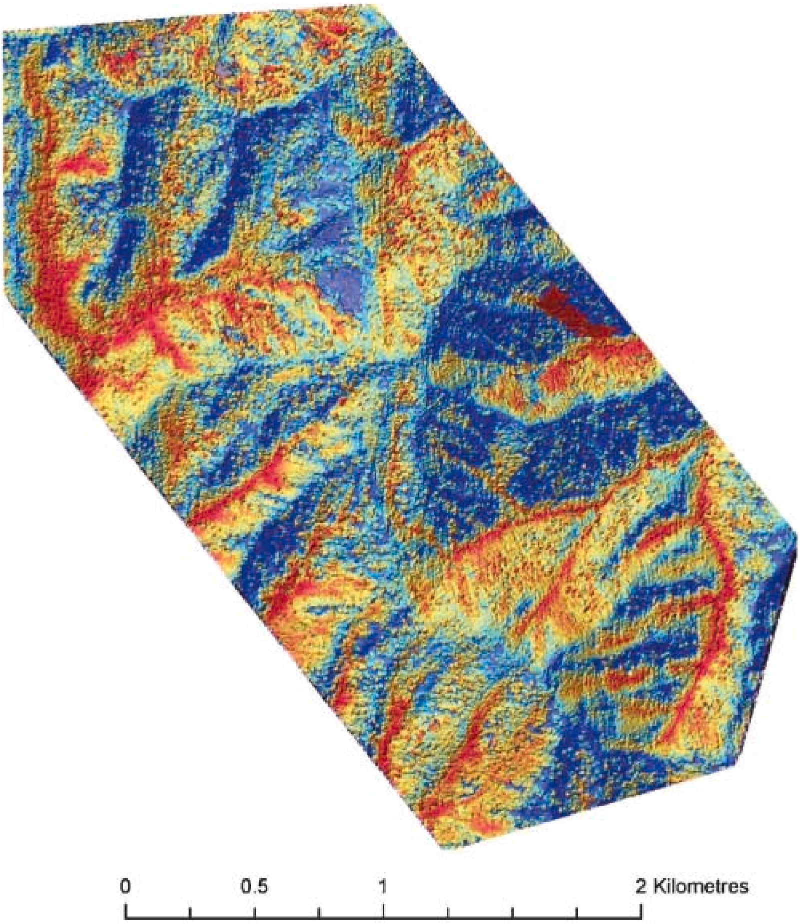

Figure 7. IFSAR-derived forest canopy height model, 1.25-m resolution (all looks, 4500 m flying height, oversampling factor of 8), draped on lidar terrain model (blue is low canopy, red is high canopy).

underestimation is inversely related to canopy density (Izzawati *et al.* 2006). In order to assess the influence of canopy density on the accuracy of IFSAR canopy heights, differences between IFSAR- and lidar-derived height models were grouped by canopy density class (derived from lidar) and summarized in table 6.

Table 1. Differences between IFSAR- and lidar-derived height estimates for 4500 m and 6000 m flying heights, using data from single passes at each height and an oversampling factor of 8 (IFSAR—lidar, in metres).

	Canopy height				Maximum height			
	Mean	SD	Median	QD	Mean	SD	Median	QD
6000 m AGL	−7.5	4.9	−7.2	2.9	−10.7	6.9	−10.3	2.9
4500 m AGL	−7.0	4.9	−6.7	2.8	−10.2	6.3	−9.9	3.6

AGL, above ground level.

Table 2. Differences between IFSAR- and lidar-derived height estimates using data from a single pass acquired at a 4500 m flying height with four different levels of interferogram filtering (IFSAR—lidar, in metres).

	Canopy height				Maximum height			
	Mean	SD	Median	QD	Mean	SD	Median	QD
OSF 1	−6.5	4.4	−6.1	2.2	−1.6	9.6	−2.5	4.4
OSF 2	−6.5	4.5	−6.0	2.3	−2.7	9.5	−3.3	4.3
OSF 4	−6.5	4.6	−6.1	2.5	−4.1	8.6	−4.6	4.3
OSF 8	−7.0	4.9	−6.7	2.8	−10.2	6.3	−9.9	3.6

OSF, oversampling factor.

Table 3. Differences between IFSAR- and lidar-derived height estimates. IFSAR collected at multiple passes at 4500 m flying height (two side looks from same direction, two orthogonal looks, opposite look directions, and combination of all looks). Oversampling factor of 8 (IFSAR—lidar, in metres).

	Canopy height				Maximum height			
	Mean	SD	Median	QD	Mean	SD	Median	QD
Side looks	−3.2	4.9	−3.2	2.9	−5.4	7.5	−5.8	3.6
Opposite looks	−2.2	3.5	−2.5	2.0	−4.4	5.5	−5.0	2.6
Orthogonal looks	−1.6	4.1	−1.6	2.1	−3.4	7.1	−4.2	2.8
All looks	−0.6	3.9	−0.8	2.0	−2.1	7.1	−3.2	2.9

Table 4. Differences between IFSAR- and lidar-derived height estimates across a range of slope classes. IFSAR collected on a single pass at 4500 m flying height with an oversampling factor of 8 (IFSAR—lidar, in metres).

	Canopy height				Maximum height			
Slope class	Mean	SD	Median	QD	Mean	SD	Median	QD
0–10°	−5.7	2.7	−5.9	1.6	−7.8	5.1	−8.4	2.9
10–20°	−5.7	3.4	−5.5	1.9	−8.3	4.4	−8.6	2.5
20–30°	−6.6	4.3	−6.3	2.6	−9.4	5.4	−9.0	3.3
30–40°	−7.3	5.3	−7.2	3.0	−10.8	6.9	−10.6	4.0
40–50°	−8.5	5.6	−7.4	3.8	−11.7	6.6	−11.1	3.6

Table 5. Differences between IFSAR- and lidar-derived height estimates across a range of slope classes. IFSAR generated from a combination of all looks acquired at a flying height of 4500 m, with an oversampling factor of 8 (IFSAR—lidar, in metres).

	Canopy height				Maximum height			
Slope class	Mean	SD	Median	QD	Mean	SD	Median	QD
0–10°	−2.9	1.8	−3.2	0.8	−3.1	6.5	−4.5	3.5
10–20°	−2.1	2.9	−2.3	1.5	−4.0	5.3	−5.2	2.4
20–30°	−0.9	3.3	−1.1	1.8	−2.5	7.3	−3.6	2.5
30–40°	−0.2	4.1	−0.3	2.1	−1.7	7.7	−2.7	3.0
40–50°	−0.2	4.3	0.5	2.6	−0.7	5.6	−1.1	3.3

Table 6. Differences between IFSAR- and lidar-derived height estimates across a range of lidar-derived canopy density (% canopy cover, or %CC) classes. IFSAR generated from a combination of all looks acquired at a flying height of 4500 m, with an oversampling factor of 8 (IFSAR—lidar, in metres).

	Canopy height				Maximum height			
%CC	Mean	SD	Median	QD	Mean	SD	Median	QD
0–10	5.7	4.1	4.9	2.8	3.1	12.8	1.1	6.2
10–20	2.7	4.5	2.0	2.7	−2.9	6.5	−4.0	3.0
20–30	0.8	7.7	0.6	2.8	−1.6	8.3	−1.8	4.2
30–40	−0.0	5.4	−0.1	3.2	−1.2	9.0	−2.9	4.2
40–50	0.3	5.8	0.2	2.8	1.0	13.2	−0.8	4.2
50–60	−1.0	5.2	−1.4	2.7	−1.1	8.0	−2.5	3.7
60–70	−0.7	3.4	−1.0	2.1	−0.8	9.2	−2.7	3.2
70–80	−1.1	3.3	−1.3	2.2	−1.9	6.4	−3.1	2.8
80–90	−0.8	3.1	−0.8	1.7	−3.0	5.4	−3.7	2.5
90–100	−0.5	2.6	−0.6	1.5	−2.7	3.6	−3.1	2.2

3.6 *Estimation of canopy cover*

A scatterplot showing the correspondence between lidar- and IFSAR-derived estimates of fractional canopy cover for the merged surface generated from all four look directions (flying height of 4500 m, standard filtering level of 8) is shown in figure 8.

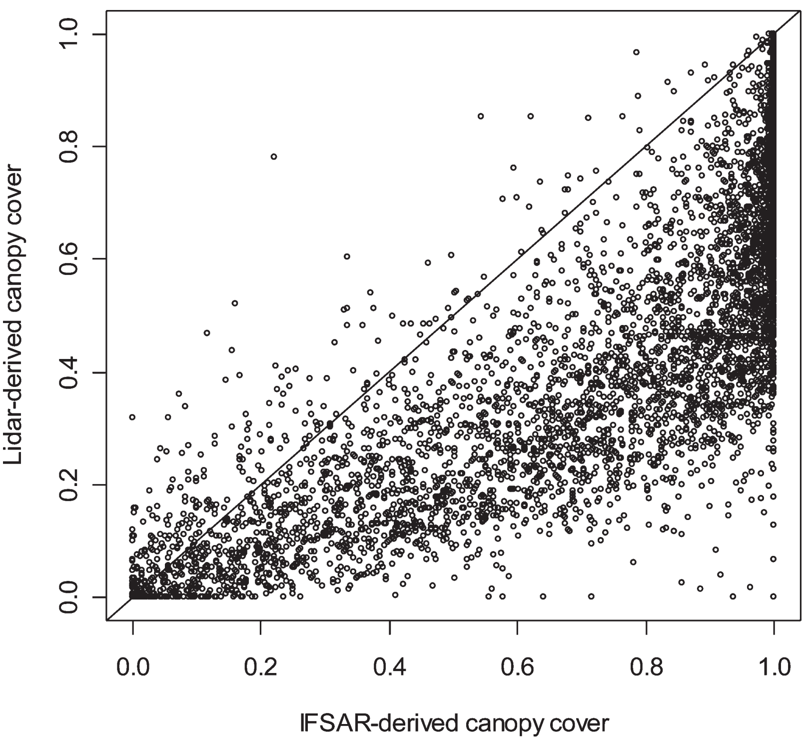

Figure 8. Comparison of lidar- and IFSAR-derived forest canopy cover estimates for 30-m grid cells. IFSAR generated from a combination of all looks acquired at a flying height of 4500 m, with an oversampling factor of 8. Line indicates 1 : 1 relationship.

3.7 *Graphical comparison of canopy height models*

A 370-m long transect (figure 9) was selected for use in a graphical comparison of the IFSAR- and lidar-derived canopy height information. Figure 10 shows a comparison of a high-resolution, all-look IFSAR-derived canopy model (with the 5-m threshold for canopy cover estimation also shown), figure 11 shows a comparison of the corresponding generalized canopy height (i.e. 90th percentile height) models at a 30-m resolution, and figure 12 shows a comparison of the corresponding maximum height models at a 30-m resolution.

4. Discussion

The results shown in table 1 indicate that the difference in flying heights studied here has little effect on the accuracy of canopy height measurements. For both of the single flight lines used in this comparison of flying heights, the median error for 90th percentile canopy height measurements was approximately −7 m, with a QD of approximately 3 m. The maximum height measurements were also not significantly different at the two different flying heights. This indicates that there would be a minimal gain by acquiring IFSAR at 4500 m versus 6000 m for forest measurement purposes.

Varying the filtering parameters (table 2) does not appear to have a significant effect on the accuracy of 90th percentile canopy height measurements. The median error is approximately −6 m, with a QD of approximately 2.5 m at all filtering levels. The level of filtering does have a significant effect on the measurement of maximum height, with higher levels of filtering leading to greater underestimation of maximum canopy height. The magnitude of the median error ranges from −2.5 m (QD of 4.4 m) for the filtering level of 1 (no filtering) to −9.9 m (QD of 3.6 m) for the highest filtering level.

As expected, using a combination of several overlapping look directions (table 3) can significantly improve the accuracy of canopy measurements. Due to the shallow look angles characteristic of IFSAR sensing, measurements of forest canopy surface acquired from a single flight line will have many areas where canopy surface features

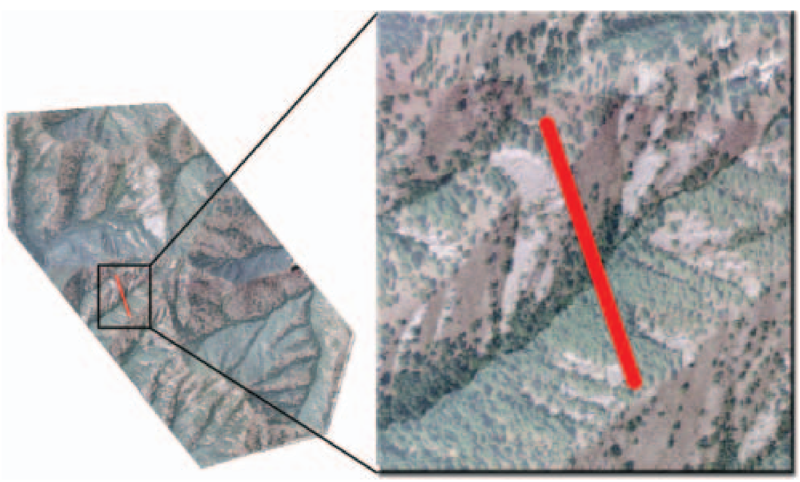

Figure 9. Location of 370-m-long transect within Mission Creek study area, Wenatchee National Forest, Washington State, USA. Available in colour online.

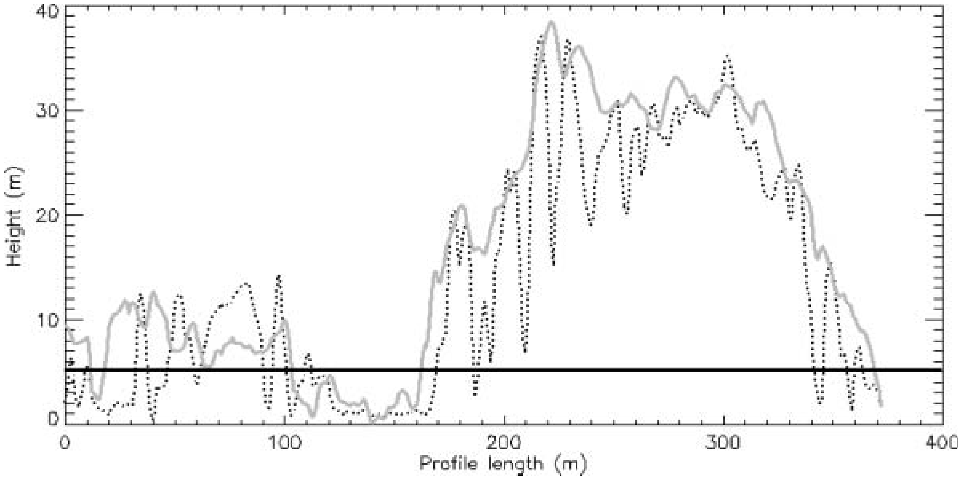

Figure 10. Comparison of high-resolution (1.25 m) canopy height models obtained from all-look IFSAR data (4500 m flying height, oversampling factor of 8) and lidar along length of transect. IFSAR surface shown as solid grey line; lidar surface is shown as dotted line. 5-m threshold height for calculation of canopy cover is also shown as a bold black line.

are fully or partially occluded by the topography and localized canopy relief. Although radar shadow areas were excluded from this analysis, it is expected that IFSAR elevation measurements will generally be most accurate in areas where the measurement is obtained from a direct reflection from an unobstructed canopy surface. Acquiring data from several different directions can help to maximize the IFSAR measurements that represent direct (optimal) measurements of the canopy surface and will therefore improve overall characterization of forest canopy surface structure. The results of this study indicate that using a combination of two different looks will generally provide a significant increase in accuracy over a single look, as the errors of the merged surfaces for all combinations of looks (median errors of −1

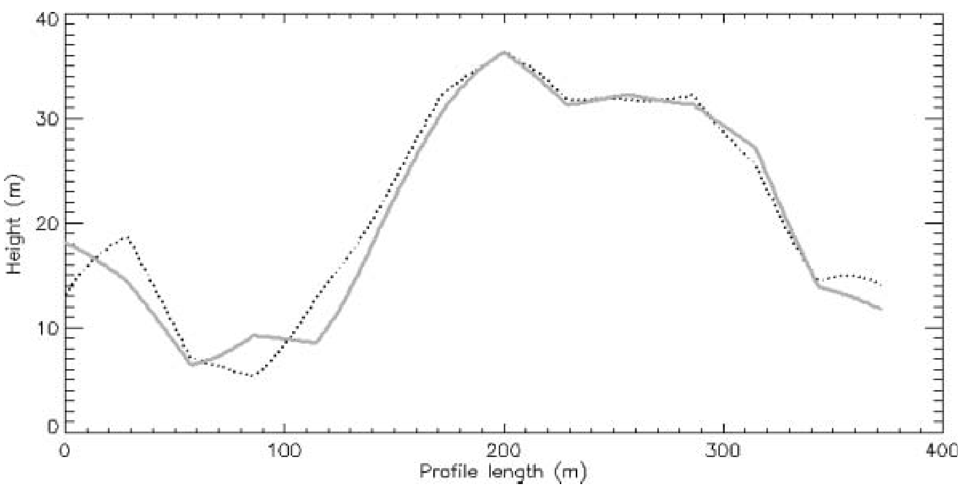

Figure 11. Comparison of generalized canopy height (90th percentile height within 30 m grid cell) for IFSAR and lidar over length of transect. IFSAR surface shown as solid grey line; lidar surface is shown as dotted line.

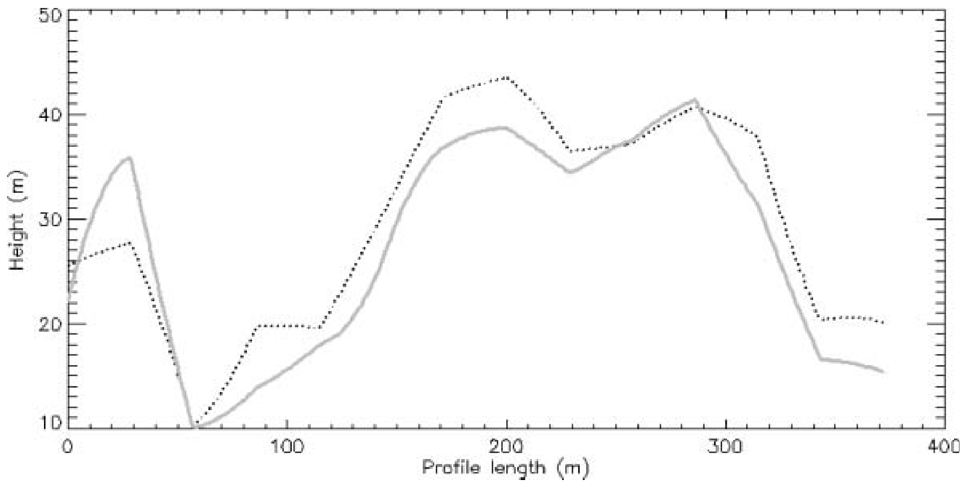

Figure 12. Comparison of maximum height models for IFSAR and lidar over length of transect. IFSAR surface shown as solid grey line; lidar surface is shown as dotted line.

to −3 m, from table 3) are lower than that for a single look (median error of −7 m, from table 1). Not surprisingly, the highest quality surface is the result of merging the data from all four looks, with a median error of −0.8 m and a QD of 2.0 m. The results indicate that acquiring IFSAR data from multiple look directions is critically important in forestry applications, especially in mountainous areas.

The results seen here provide a confirmation of previous studies: terrain slope will influence the accuracy of IFSAR canopy height estimation when IFSAR is generated from a single pass. Table 4 indicates that the accuracy of the IFSAR canopy height and maximum height measurements obtained from a single pass will decrease with increasing slope. The results also show that using IFSAR canopy models developed from a combination of looks will largely mitigate the effects of slope on the accuracy of canopy measurements. The results in table 5 indicate that the use of multiple look IFSAR data reduced the underestimation of canopy height at higher slopes (−3.2 m median error in canopy height at 0–10° to +0.5 m median error at 40–50°), but there is increased random error in the height measurements as the slope increases (0.8 m QD at 0–10° to 2.6 m QD at 40–50°). It should be noted that the effects of slope and canopy density are somewhat difficult to separate, as canopy density is certainly influenced by the terrain slope in this area (i.e. low canopy densities on dry ridge crests, high canopy density in moist drainages).

The results of this study also indicate that the accuracy of IFSAR canopy height measurements will be heavily influenced by canopy density (see table 6). In low density areas, the IFSAR measurements do not capture gaps between the trees, and canopy height represents measurements in the upper portion of the tree crown, while the lidar canopy height is more influenced by canopy openings, leading to an overestimation of generalized canopy height in the IFSAR models (4.9 m median error and 2.8 m QD in 0–10%CC class). It should be noted that this result runs counter to the findings of Izzawati *et al.* (2006), where height underestimation increased with decreasing canopy density. This difference in results is most likely due to the use of multiple passes of IFSAR data in our study, but this issue requires further investigation. However, we did find that the discrepancy between the lidar- and IFSAR-derived canopy height measurements decreases with increasing canopy density (with a median error of −0.6 m and QD of 1.5 m for 90–100%CC class), which is consistent with the results of previous studies.

Estimating canopy cover using only IFSAR elevation data is a difficult proposition. In general, the sensing geometry of IFSAR does not allow for accurate measurement of high frequency details in the morphology of the canopy surface, including canopy gaps and smaller individual tree crowns. In the IFSAR canopy height model, individual tree crowns tend to be smoothed, and canopy gaps are 'filled in'. Therefore, in forests with a relatively discontinuous canopy surface structure and many gaps, a canopy cover estimate derived from the IFSAR canopy height model will tend to be higher than the lidar-based canopy cover estimate, as figures 9 and 11 indicate. Because of these limitations, IFSAR (in contrast to lidar) is unlikely to be used operationally as a forest management tool, and will be more suitable for large-area resource assessment and monitoring applications.

5. Conclusion

This study confirms that X-band IFSAR has the potential to be a useful source of data in the measurement and monitoring of canopy height over large areas. The results presented here do not indicate a significant improvement in the accuracy of canopy height measurements by acquiring the data at a lower flying height, and suggest that the typical mission parameters used for high accuracy (Type II) IFSAR topographic survey may also be adequate for forest monitoring applications (Mercer 2004). The results also indicate that the accuracy of general canopy height measurements is not greatly influenced by the level of interferogram filtering, but can be highly influenced by sensing geometry. It is also shown that the accuracy of IFSAR canopy height measurements is strongly influenced by canopy density, with accuracy degrading with decreased canopy density. These findings support the conclusion that acquiring data from multiple-look directions may be the most important consideration in the planning of IFSAR flights for forest monitoring applications, while it should be expected that IFSAR-derived canopy height information will be most reliable in forests with dense canopies. While estimation of canopy cover is difficult using only IFSAR height data, it is expected that results could be improved significantly through use of the texture information obtained from high resolution X-band backscatter images, which are standard deliverables in an IFSAR acquisition.

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